Journal of Environmental Science and Engineering B 15 (2026) 89-104
doi:10.17265/2162-5263/2026.02.004

Quantifying the Energy Efficiency of Deep Bioclimatic Buildings That Are Thermally Self-regulating

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Abstract: This study analyzes the energy efficiency of *deep bioclimatic buildings*. Buildings with deep bioclimatic design are those which are capable of self-regulating thermally, and providing a comfortable internal temperature, only due to their special bioclimatic design, and without the need for heating or air conditioning devices. This study proposes a project methodology for designing deep bioclimatic buildings and includes an energy efficiency analysis of a case study: the Silvana house, a deep bioclimatic building. The findings of this study are directly applicable to all single-family homes featuring deep bioclimatic design. This specific design ensures a comfortable indoor temperature without requiring mechanical heating or air conditioning. Furthermore, the results offer insights into the energy efficiency potential of deep bioclimatic design when applied to different building types and diverse environmental conditions.

Key words: Bioclimatic design, passive design, insulation, thermal inertia, energy efficiency.

1. Introduction

The initial oil crises of the 1970s prompted the development and design of bioclimatic buildings. The primary goal was to minimize building energy consumption as much as possible, particularly for heating and air conditioning. These buildings were sometimes capable of thermal self-regulation, which eliminated the need for heating or air conditioning and resulted in maximum energy savings [1-4].

Bioclimatic building design demands extensive technical knowledge and significant project expertise from architects. Consequently, the actual outcomes sometimes fall short of the initial predictions.

Manufacturers, on the other hand, immediately seized the opportunity to produce devices with improved thermal efficiency. Bioclimatic design began to play a secondary role, and the idea began to emerge that sustainable and highly energy-efficient buildings were conventional buildings, with a little more insulation, and equipped with high-energy-efficiency heating and air conditioning equipment. The commercial interests of these manufacturers started to ignore bioclimatic design, leading to the proposal of the term "passive design". This clearly shows their desire to relegate bioclimatic design to a secondary role and, instead, emphasize the mass incorporation of building technologies. As a result, most standards, laws and GBRS (*green building rating systems*) place excessive value on the integration of high-energy-efficiency devices in buildings, while barely valuing the energy efficiency of bioclimatic design (or not valuing it at all) [5, 6].

Effective bioclimatic design can significantly improve a building's energy efficiency and sustainability by eliminating the need for heating and air conditioning equipment. This is a crucial goal, as the current state of building design is still significantly lacking in this

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regard. Furthermore, the added cost inherent in the design of bioclimatic buildings is equivalent to the added cost of the heating and air conditioning units currently installed in buildings. For this reason, some architects, despite the current oppressive and alienating regulatory framework, continue to design bioclimatic buildings [7].

However, the energy efficiency that can be achieved depends on the thermodynamic and energetic knowledge of the architects, and above all on their professional talent and expertise. This approach can sometimes lead to a modest decrease in energy use, and in other instances, it can completely remove the necessity for incorporating heating and air conditioning systems within the buildings.

In the context of this study, *deep bioclimatic design* is defined as one that allows buildings to thermally self-regulate, generating comfortable interior temperatures without the need for heating or air conditioning devices [8, 9].

Deep bioclimatic design requires architects to have in-depth knowledge of thermodynamic behavior of buildings and considerable experience, enabling them to continuously test the architectural strategies that enable successful bioclimatic design. While the complete elimination of heating or air conditioning may not always be possible, minimizing their power consumption provides the greatest energy savings and simultaneously maximizes thermal comfort [10-12].

In any case, deep bioclimatic architecture has enormous environmental benefits, since in addition to reducing energy consumption [13-15], it reduces waste and emissions [8, 16, 17], increases the sustainable level to the maximum [18-21], improves health and well-being [22, 23], reduces the costs and maintenance of social housing, and greatly facilitates self-sufficiency [8].

2. Method. Deep Bioclimatic Buildings

A bioclimatic building's careful and specific design allows for the reduction of energy consumption to varying degrees, regardless of its location. However, designing a *deep* bioclimatic building implies a more rigorous process, and it is not always possible, at least without substantial economic increase. Designing deep bioclimatic buildings requires a specific, rigorously followed project methodology. Given the complexity of translating mathematical requirements into a tangible architectural structure, projectual expertise and experience are crucial. This complex task often yields multiple, yet equally valid, architectural solutions.

2.1 Deep Bioclimatic Design Methodology

Achieving a building that is thermally self-regulating—maintaining a comfortable interior temperature continuously without reliance on heating or air conditioning systems—requires a meticulous and comprehensive design strategy. Every phase and detail of the design process must be scrupulously examined. The extensive bioclimatic design process generally encompasses a minimum of the following stages [9, 14]:

1. Obtaining environmental and climatological data;
2. Obtaining the angles of solar radiation at the solstices and equinoxes;
3. Study of variations in humidity and temperature in the psychometric diagrams;
4. Pre-dimension of energy losses and of solar radiation gains;
5. Pre-sizing of the area and position of the glass surfaces;
6. Obtaining the general parameters of a building from psychometric diagrams;
7. Generating the first sketches integrating all the requirements;
8. Proposal for the most appropriate architectural typology;
9. Progressive refinement of architectural typology;
10. Definition of the main architectural bioclimatic strategies;

11. Achieving a balance between bioclimatic energy gains and losses;

12. Calculation of solar shading;

13. Most appropriate construction solutions;

This methodology has been successfully applied in the design of *deep bioclimatic buildings*, capable of thermally self-regulating and providing a comfortable indoor temperature, without the need for heating and air conditioning devices [5, 19, 21, 24].

2.1.1 *South Orientation. Distribution of Solar Radiation*

The first fundamental step that must be taken into account throughout the entire design process of a deep bioclimatic building is that it should have a "south-orientation" (north orientation in the south hemisphere).

The south-orientation of a building seems simple, but is actually complex, as it must have at least the following characteristics [9, 14].

1. The building must be designed linearly along the east-west axis to maximize solar radiation in winter and be protected from it in summer by means of adequate horizontal and vertical solar shading.

2. The building's most important rooms (served spaces) should be located on the south side, and the auxiliary rooms (serving spaces) on the north side. By locating the most important spaces on the south side, they are easier to heat with solar radiation and, at the same time, can be cooled by fresh air currents generated along the north side.

3. The south facade must have an exact orientation, east-west, so that the solar shading systems are as effective as possible (in summer) and maximize the use of solar radiation (in winter). Therefore, it is very important to have no setbacks on the south facade, to prevent overhangs from shading and obstructing the entry of solar radiation to the windows in winter.

4. Most of the glazed surfaces should be located on the south side, with very few on the north side, and they should be avoided on the east and west sides.

2.1.2 *Analysis of the Incidence of Solar Radiation in Winter on a South-Facing Building*

In winter, solar radiation is inclined slightly relative to the horizontal plane, so most of the solar radiation falls on the south face. In contrast, the east and west faces receive little solar radiation. The east face receives only a few hours of solar radiation in the morning, and the west face only a few hours in the afternoon. The roof receives radiation throughout the day, but with less intensity than the south face, due to the inclination of the sun's rays (Fig. 1).

The drawing shows the duration of exposure to solar radiation, and the maximum intensity of solar radiation that hits each side, in relation to the maximum intensity of solar radiation that hits the roof in summer. The relative proportion between the solar index inside the center, above, and above and below is only an average with illustrative purposes, as it will depend on the latitude of the location of a specific building.

2.1.3 Analysis of the Incidence of Solar Radiation in Summer on a South-Facing Building

In summer, solar radiation is highly inclined relative to the horizontal plane, so most of the solar radiation falls on the roof. The roof receives solar radiation all day, from sunrise to sunset. The south facade receives solar radiation for only 12 hours, but with less intensity than on the roof, due to the high inclination of solar radiation. The east facade receives solar radiation from sunrise until midday, and the west facade from midday until sunset. On the north facade, and depending on the latitude, solar radiation is measured just a few hours after sunrise and just a few hours before sunset (Fig. 2).

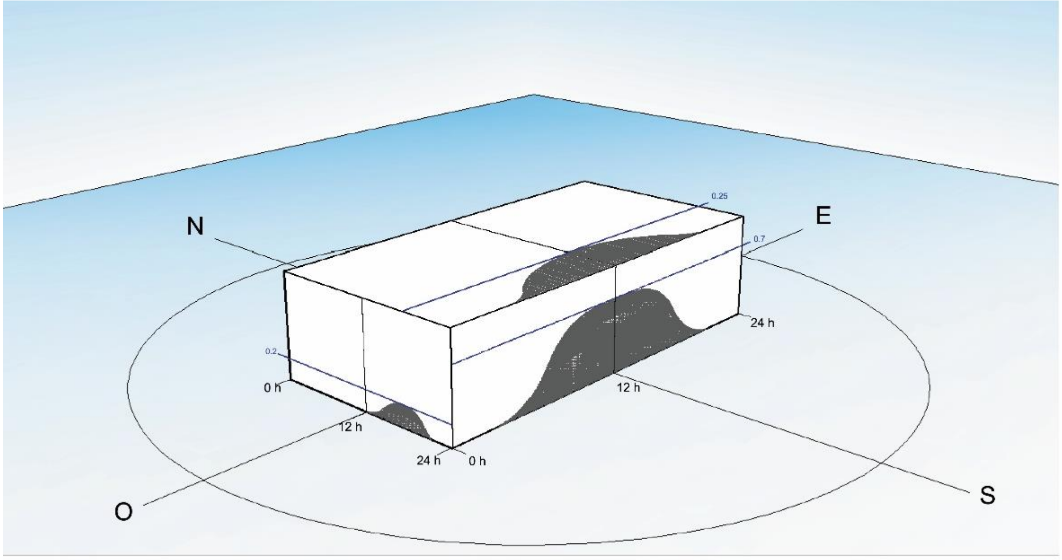


Fig. 1 Incidence of solar radiation in winter on a south-facing building (drawing Luis de Garrido).

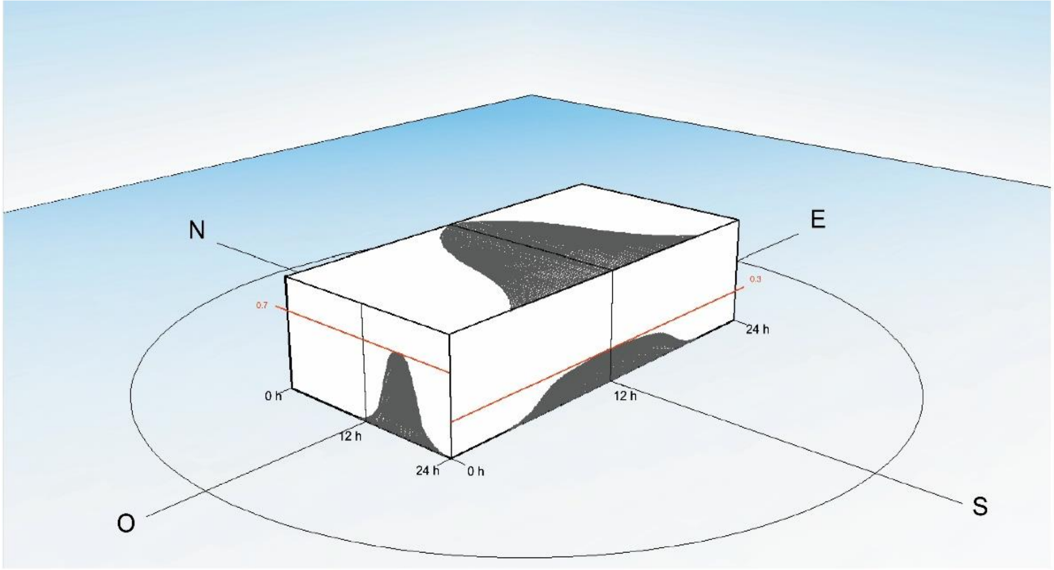


Fig. 2 Incidence of solar radiation in summer on a south-facing building (drawing Luis de Garrido). The drawing shows the duration of exposure to solar radiation, and the maximum intensity of solar radiation that hits each side, in relation to the maximum intensity of solar radiation that hits the roof in summer. The relative proportion between the solar index inside the center, above, and above and below is only an average with illustrative purposes, as it will depend on the latitude of the location of a specific building.

2.1.4 Design Guidelines Considering the Distribution of Solar Radiation in South-Facing Buildings

As a result of this analysis of the incidence of solar radiation, important guidelines can be deduced for the proper bioclimatic design of a building. These guidelines must be taken into account from the initial sketches until the end of the design process.

1. Glazed surfaces should never be installed on roofs, as they provide little solar thermal gain in winter and, while, contribute to significant thermal loads in summer.

2. Glazed surfaces should be installed primarily on the south facade to maximize solar radiation in winter and, at the same time, to design effective solar shading

in summer and prevent solar radiation from entering the building through the windows. By properly shading the building from direct and indirect radiation, the amount of radiation that is intended to enter the building every day of the year can be controlled.

3. Glazed surfaces should not be installed on either the east or west sides of deep bioclimatic buildings. In winter, hardly any solar radiation reaches the east and west sides, so it's not worth installing windows, allowing excessive amounts of solar radiation to enter in summer.

4. As few windows as possible should be installed on the north side, and only when absolutely necessary. Glass windows always have poor thermal insulation (compared to enclosures), so they always cause energy losses in winter (and thermal gains in summer).

5. Vertical windows can be installed above the roof, provided they have appropriate vertical and horizontal solar shading. These windows can effectively help heat the building in winter but allow very little solar radiation to enter in summer. They can also create a strong "chimney effect" to evacuate hot air from the upper part of the building's interior, while allowing fresh air currents to enter.

This conceptual analysis establishes a set of initial strategies that must be integrated into the overall deep bioclimatic design methodology. of the incidence of solar radiation on the faces of a deep bioclimatic building allows to establish a set of basic initial strategies that must be considered from the first drafts of a given building's design and that must be integrated into the overall deep bioclimatic design methodology (especially from Stages 4 to 9).

2.2 Thermodynamic Equilibrium of Energy Gain and Loss

2.2.1 Reducing a Building's Energy Losses

A building's energy losses Q_l are calculated very simply [14]:

$$Q_l = \sum_n \left(K_n * S_n * (t_{int} - t_{ext})\right)$$

where Q_l is the energy loss of a building, with n differentiating elements in its architectural envelope; K_n is the thermal transmission coefficient of each differentiating element of the architectural envelope; Sn is the surface area of each differentiating element of its architectural envelope; and $(t_{int} - t_{ext})$ is the difference between the interior and exterior temperatures of the building.

Therefore, energy losses can be reduced by using highly insulating (K) and compact (S) architectural envelopes, and by not being too demanding on the interior comfort temperature (t_{int}). This minimizes the energy consumption of heating and air conditioning systems, which must provide an energy Q_g similar to the losses at all times ($Q_g = Q_l$). As can be seen from the mathematical formula, if Q_l is positive the building loses heat ($t_{int} > t_{ext}$), while if Q_l is negative the building gains heat ($t_{int} < t_{ext}$).

When designing a deep bioclimatic building, energy requirements must be minimized as much as possible, since the building must be heated and cooled by natural means, without machinery. Therefore, energy losses are minimized, while other complementary conditions are also met to ensure the building's optimal thermodynamic behavior [9, 20].

2.2.2 Bioclimatic Energy Gains

To counteract the energy losses ($+Q_l$) of a given building, or gains ($-Q_l$), devices are typically used that provide a certain amount of energy ($+Q_g$) (heating appliances) or absorb it ($-Q_g$) (air conditioning appliances). Obviously, all these devices consume energy of one type or another.

However, it is also possible to design buildings that can generate the energy needed to heat themselves ($+Q_g$) by harnessing direct solar radiation and the greenhouse effect. It is also possible to design buildings that can cool themselves by absorbing energy ($+Q_g$) using the cool night air (which is further cooled through underground ducts where the temperature is much lower).

With proper architectural design, a building's thermal demands can be met, as in winter the building can generate heat inside, and in summer it can generate cold inside, without the need for appliances [9, 19, 20].

2.3 Architectural Typologies and Strategies for Generating Heat and Cooling

Deep bioclimatic design utilizes all available natural energy resources. To achieve this, architects integrate highly effective architectural strategies into their designs to maximize their use.

In general, in winter, the available solar radiation, however small, is maximized. To do this, buildings should be south-facing and incorporate south-facing glazed surfaces to generate a powerful greenhouse effect. This heat, continuously generated during the winter days, must be stored internally to continue warming them throughout the night.

In summer, the design takes advantage of the nighttime temperature drop and the temperature decrease in the subsoil. During the night, buildings are ventilated internally and gradually cool down. To maintain the building's coolness throughout the subsequent day, the produced coolness must be internally stored. Therefore, buildings must also be protected as much as possible from direct and indirect solar radiation through fixed and movable solar shading integrated into the building design. In most climatic environments, deep bioclimatic buildings can be achieved provided the architect has the appropriate expertise and knowledge. In the most extreme climates, deep bioclimatic buildings can also be achieved, but at a much higher cost than if they were equipped with technological devices. Therefore, in these cases, it is cheaper and more sensible to implement a proper bioclimatic design in order to minimize the power required for heating and air conditioning.

2.3.1 Architectural Systems for Generating Heat

Deep bioclimatic buildings can thermally self-regulate in winter and generate heat inside to achieve an adequate temperature. Achieving this requires a specific design and the correct south-orientation, as previously mentioned. During the day in winter, the design ensures that solar protections are retracted, maximizing the solar radiation that penetrates the building's interior through its glass surfaces. In this way, the interior of the buildings is heated by solar radiation and the greenhouse effect. The surface area of the glass must be carefully calculated (as well as its location and shape) to allow the passage of sufficient solar radiation to satisfy the thermal demands of its occupants. Consequently, buildings must be highly insulated and carefully designed to minimize their energy consumption. Furthermore, the heat generated during the day must be accumulated inside the buildings so that it can be conserved throughout the night. A variety of design strategies exist to manage internal heat generation in buildings; these should be implemented progressively until the building's specific thermal requirements are satisfied. In colder environments, the architectural design must be more refined and incorporate a greater number of strategies to ensure adequate and natural heating of the building interiors.

2.3.2 Architectural Systems for Generating Cooling

Thermally self-regulating, *deep bioclimatic buildings* can achieve a comfortable interior temperature in the summer by generating their own cooling. To achieve this, they must have a correct south-facing orientation and an appropriate bioclimatic design. Based on this design, in summer, during the night, the interior of buildings must be adequately ventilated to cool them internally until they reach the outdoor nighttime temperature. The coolness accumulated inside the buildings must be maintained throughout the following day. Therefore, the building must have all types of solar protection and optimized architectural ventilation and cooling systems to maintain the coolness of the night throughout the following day. Nighttime temperatures may be higher than the comfort temperature (over 25 °C), so the outdoor ventilation air must be further cooled through complementary architectural strategies. One of the most effective approaches is to incorporate underground galleries into the building design to further cool the nighttime outside air before introducing it into the buildings for cooling. Of course, the nighttime cooling process must be carried out for as long as necessary, and at the time when the outside temperature is lowest (usually about 6 hours, between 1 and 7 a.m.).

Therefore, it is possible to heat and cool buildings without the need for appliances. Furthermore, the additional cost of constructing the necessary architectural systems can be, and should be, less than the economic cost of the appliances they replace. Undoubtedly, deep bioclimatic building design is fascinating, and its ecological and sustainable advantages are unsurpassed.

However, for natural heating and cooling architectural systems to be effective, one fundamental condition must be guaranteed: insulation must always be located on the exterior of the architectural envelope, and the heavier the buildings, the better. It should be noted that greater weight does not imply greater economic costs, as the weight can be increased simply by using construction waste or soil from the excavation itself.

3. Results. Case Study: Silvana House

In order to analyze the energy and sustainability benefits of *deep bioclimatic buildings*, the thermodynamic behavior of a *deep bioclimatic house* is analyzed in depth. This house does not require air conditioning or heating devices to maintain a comfortable internal temperature every time. Consequently, the house consumes little energy, making it very economical to convert it into an energy self-sufficient house.

3.1 General Information

Silvana house is located in Valencia (Spain), has a constructed area of 321.76 m^2 on two floors (Figs. 3, 4, 5, 6), and a basement. The usable surface is 269.9 m^2. The ground floor has a central double-height patio, a living room, four bedrooms, three bathrooms, a kitchen, a studio and a laundry room (Fig. 7). The first floor has a main bedroom with a dressing room and a bathroom, with access to the two lateral green roofs (Fig. 8).

Silvana house was built in 2022 and thanks to its special *bioclimatic design* is capable of maintaining a comfortable interior temperature, so that its average energy consumption is 66.5% less than that of a conventional house of the same surface area and characteristics. It also does not need lighting during the day nor ventilation devices. Due to its low energy consumption, *Silvana* house is self-sufficient in energy and water at a very low price.

Fig. 3 ***Silvana eco-house*. Valencia. Spain (Projected by Luis de Garrido). South façade.**

Fig. 4 ***Silvana eco-house*****. Castellón. Spain (Projected by Luis de Garrido). North façade.**

Fig. 5 ***Silvana eco-house*****. Valencia. Spain (Projected by Luis de Garrido).**

Fig. 6 The *Silvana* house does not require any heating equipment to maintain a comfortable internal temperature. However, this is only equipped with a small biomass stove for the coldest days of the year.

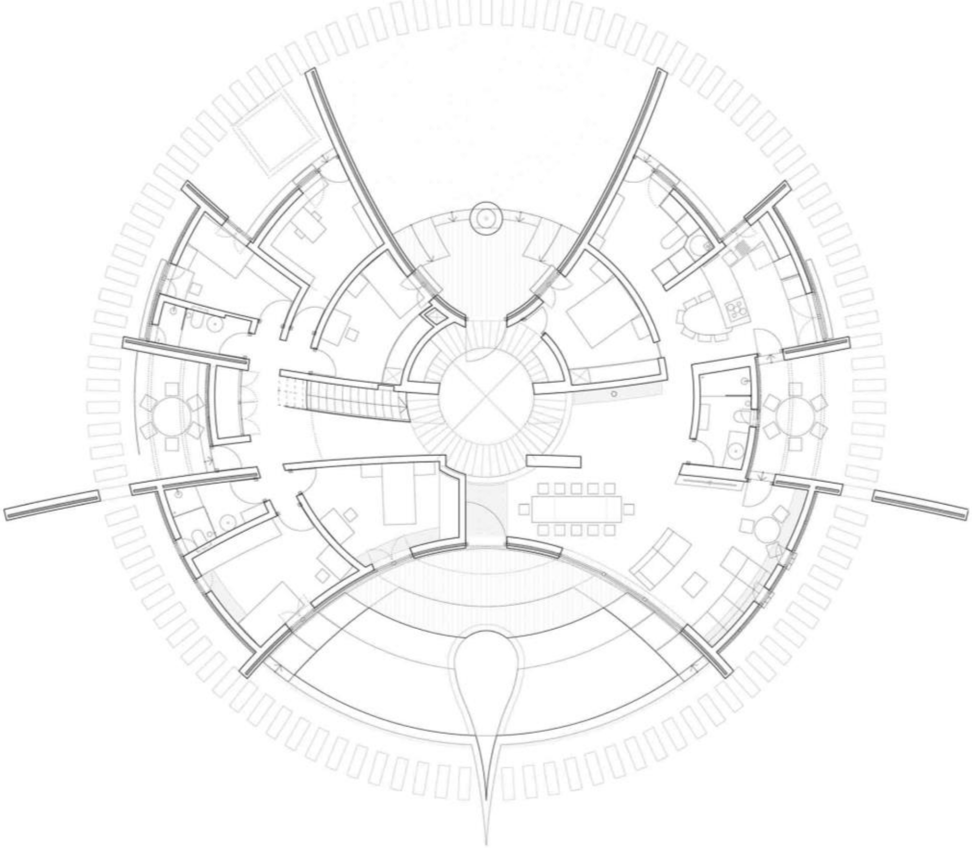


Fig. 7 *Silvana* house. Ground floor layout.

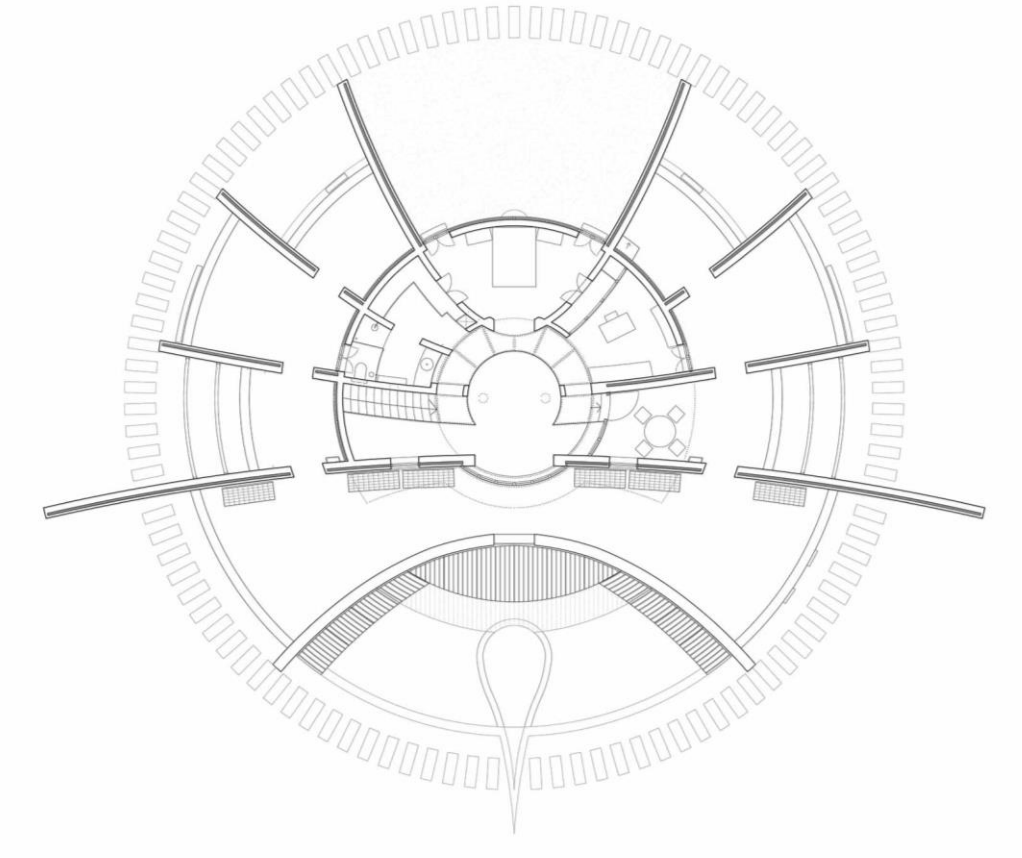


Fig. 8 ***Silvana*** **house. First floor layout.**

3.2 Deep Bioclimatic Design

In this study, *deep bioclimatic design* is defined as creating buildings capable of thermal self-regulation, providing a comfortable interior temperature (19 °C-25 °C), without the need for heating and air conditioning equipment. Achieving this requires good professional skills, although in extreme climates, occasional heating may still be needed. The energy savings of bioclimatic design are often measured as the "bioclimatic level". In this article, we focus on a 100% bioclimatic approach, in which the *Silvana* house demonstrates the ability to provide comfortable indoor temperatures without any mechanical devices.

3.2.1 Bioclimatic Heating

The house's design incorporates several special features that enable it to heat itself in winter (Fig. 9), such as the following:

- North-south orientation;
- Most windows on the south façade;
- High thermal inertia on the internal side of the enclosure;
- Adequate insulation on the external side of the enclosure;
- Adequate greenhouse effect that generates the required heat energy;
- Solar protections allow maximum solar radiation to enter the building in winter;
- Main rooms are located on the south and service rooms on the north.

The windows located on the south of the house (with an area of about 32 m^2) (Fig. 9) generate about 11,200 W of heating on average in winter (since about 350 W/m^2 pass through the glass) (350 * 32 = 11,200). The occupants of the house and the energy losses from the refrigerator and other appliances provide an additional 1,500 watts of heating. In other words, the house is capable of generating about 12,700 W of heating power, which is enough to heat its rooms (see

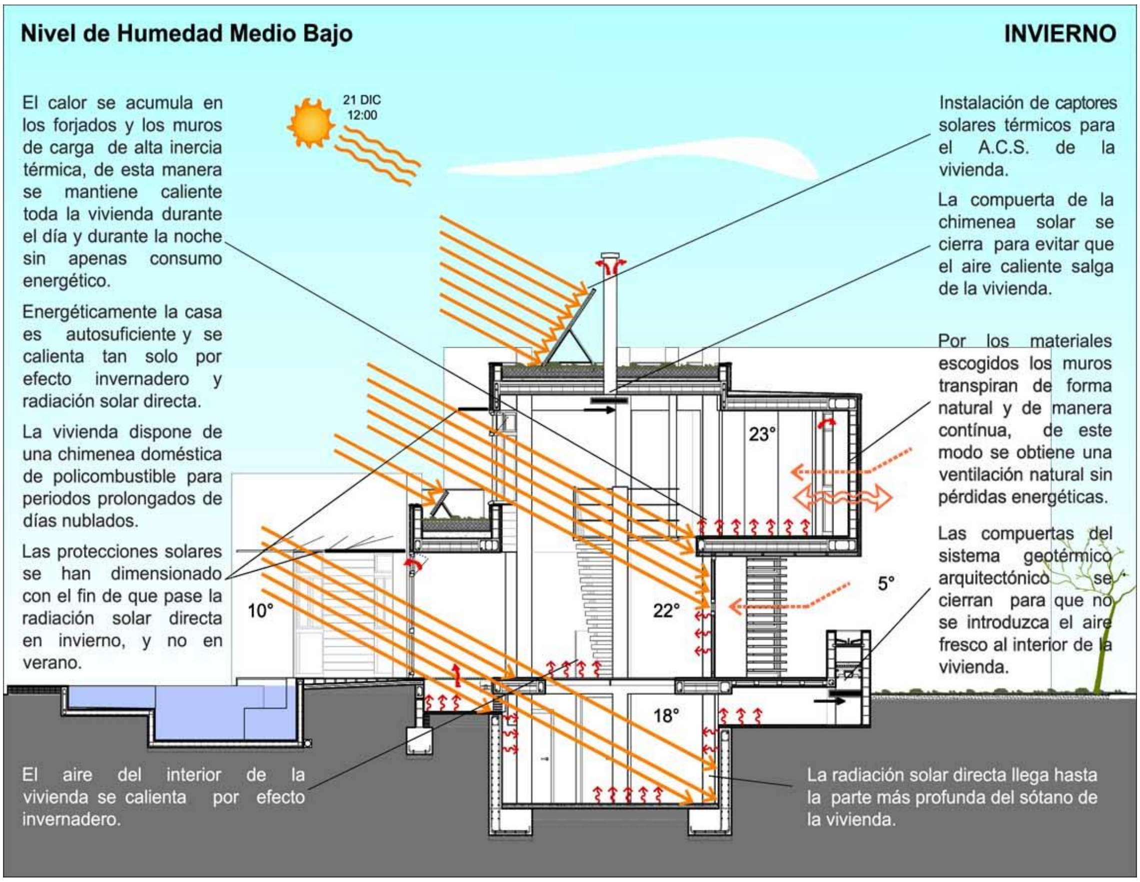
3.3.2). *Silvana* house thus maintains a minimum temperature inside of 19 ºC in winter.

3.2.2 Bioclimatic Cooling

The house cools itself in summer by several special features of its design (Fig. 10), among which the following stand out:

- North-south orientation;
- High thermal inertia on the internal side of the enclosure;
- Adequate insulation on the external side of te enclosure;
- Cold generation in underground galleries;
- Cold generation through optimized internal night ventilation;
- Solar protections allow minimum solar radiation to enter the building in summer;
- Served spaces to the south, serving spaces to the north.

Firstly, the house cools down in summer, avoiding heating up during the day, due to its orientation, the arrangement of glass and the special solar protections. Secondly, the house is designed to use cold night air. This air is further cooled in underground galleries and penetrates the interior, cooling it during the night. The house then remains cool during the day due to solar protections, high interior thermal inertia, and its exterior insulation. A maximum internal temperature of about 25 ºC is maintained in summer during daylight and 18-21 ºC during the night.



Nivel de Humedad Medio Bajo

INVIERNO

El calor se acumula en los forjados y los muros de carga de alta inercia térmica, de esta manera se mantiene caliente toda la vivienda durante el día y durante la noche sin apenas consumo energético.

Energéticamente la casa es autosuficiente y se calienta tan solo por efecto invernadero y radiación solar directa.

La vivienda dispone de una chimenea doméstica de policombustible para periodos prolongados de días nublados.

Las protecciones solares se han dimensionado con el fin de que pase la radiación solar directa en invierno, y no en verano.

El aire del interior de la vivienda se calienta por efecto invernadero.

Instalación de captores solares térmicos para el A.C.S. de la vivienda.

La compuerta de la chimenea solar se cierra para evitar que el aire caliente salga de la vivienda.

Por los materiales escogidos los muros transpiran de forma natural y de manera contínua, de este modo se obtiene una ventilación natural sin pérdidas energéticas.

Las compuertas del sistema geotérmico arquitectónico se cierran para que no se introduzca el aire fresco al interior de la vivienda.

La radiación solar directa llega hasta la parte más profunda del sótano de la vivienda.

Fig. 9 ***Silvana*** **house. Special bioclimatic architectural design to heat the interior of the house in winter without the need for heating devices.**

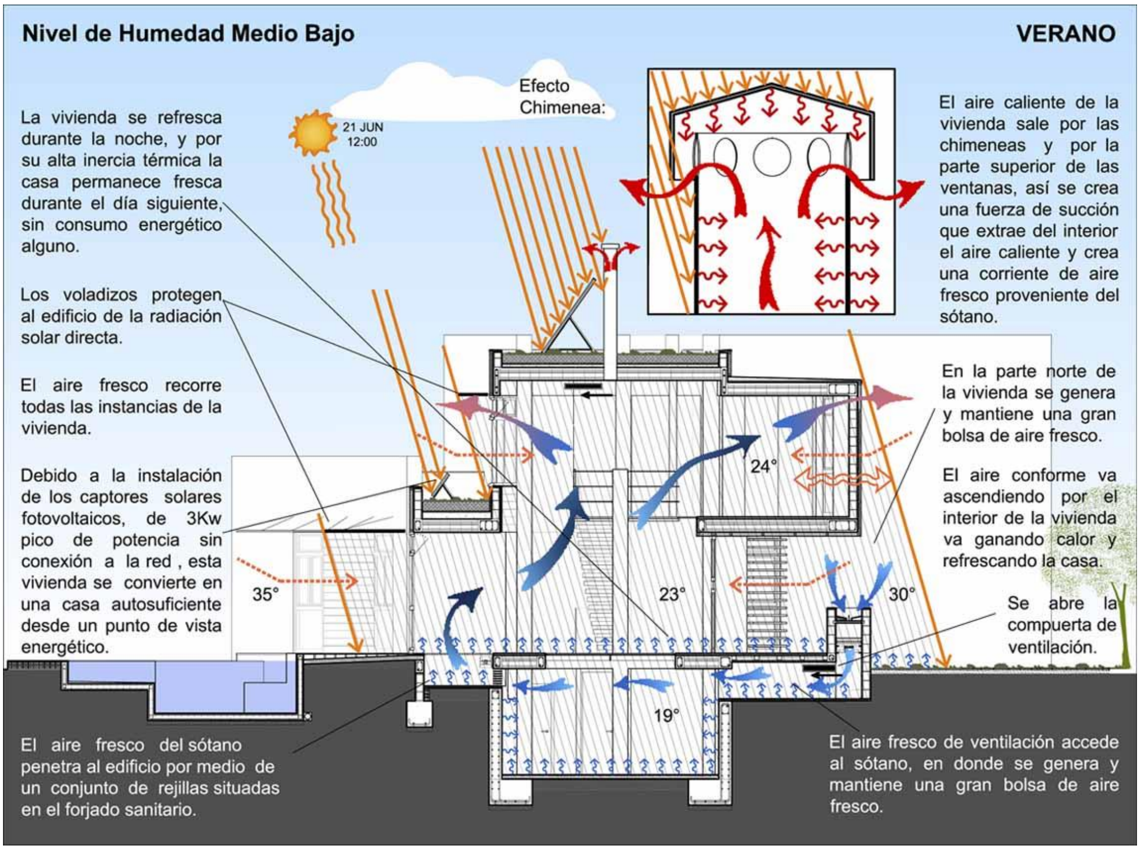


Fig. 10 ***Silvana*** **house. Special bioclimatic architectural design to cool the interior of the house in summer without the need for air conditioning devices.**

3.3 Quantification of the Energy Efficiency of a Deep Bioclimatic House. Silvana House

To quantify the energy efficiency of a deep bioclimatic house, the energy consumption of the *Silvana house* is compared with the energy consumption of a conventional house of the same characteristics constructed in the same area. To be able to make a comparison we have compared *Silvana house* with respect to its hypothetical version as a baseline reference: *Silvana-no-bio*. That is, with identical characteristics, but with a conventional design and average energy needs for the area. It is clear that, depending on its design, level of insulation, and thermal inertia, each house can have a different energy consumption. Therefore, Silvana-no-bio has been assigned an average energy consumption based on existing houses in the area where the *Silvana* house is built.

3.3.1 Deep Bioclimatic House Energy Consumption. Silvana House

Due to its *deep bioclimatic design*, the house does not need heating devices, air conditioning, or mechanical ventilation, and as the owners are highly conscious of reducing energy consumption as much as possible, the house has very few appliances, with a total power of 4,524 W (Table 1) with an annual consumption of 18.21 kw h/m^2 (Table 2).

3.3.2 Conventional House Energy Consumption. Silvana-No-Bio

A conventionally designed house requires heating and air conditioning to maintain a comfortable interior temperature and artificial lighting in some of its rooms, even during the day. As a result, the house has an additional cost (price of the equipment and price of the space to house them), requires more maintenance, generates harmful emissions, and reduces the well-being and health of its occupants (noise, odors, vibrations).

Table 1 Total power of the appliances in *Silvana-bio*.

Fridge	150 W (average power)
Induction hob	1.000 W
Microwave	500 W
Washing machine	1,000 W
TVs	300 W
PCs	100 W
Lighting	210 W
Garden lighting	84 W
Water purification	1.180 W
Total power	4,524 W

Table 2 Total energy consumption per m^2 of *Silvana-bio*.

269.9 m^2	Power W (watts)	Active time (hours)	Energy per year (kwh/year)	Energy year/m^2 (kwh/m^2/year)
Fridge (average power)	150	24 h. * 365	1.31	4.86
Induction hob	1.000	2 h. * 365	730	2.70
Microwave	500	1 h. * 365	182.5	0.67
Washing machine	1,000	1 h. * 365	365	1.35
TV	300	8 h. * 365	876	3.24
PC's	100	8 h. * 365	292	1.08
Lighting	210	8 h. * 365	613.2	2.27
Garden lighting	84	4 h. * 365	122.6	0.45
Water purification	1,180	1 h. * 365	430.7	1.59

Total energy consumed per m^2: 18.21 kwh/m^2/year.

Table 3 Total energy consumption per m^2 of *Silvana-no-bio*.

269.9 m^2	Power W (watts)	Active time (hours)	Energy year (kWh-year)	Energy year/m^2 (kWh/m^2/year)
Fridge (average power)	150	24 h. * 365	1.31	4.86
Induction hob	1.000	2 h. * 365	730	2.70
Microwave	500	1 h. * 365	182.5	0.67
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TVs	300	8 h. * 365	876	3.24
PC's	100	8 h. * 365	292	1.08
Lighting	210	8 h. * 365	613.2	2.27
Garden lighting	84i	4 h. * 365	122.6	0.45
Water purification	1,180	1 h. * 365	430.7	1.59
Heating/cooling (mild temp.)	5,398	12 h. * 90	5,829	21.6
Heating/cooling (peak temp.)	10,796	12 h. * 30	3,886	14.4

Total energy consumed per m^2: 54.21 kWh/m^2/year.

The total usable surface of *Silvana-no-bio* is 269.9 m^2. In Valencia, the average power of heating and air conditioning systems is, at least, 40 W/m^2, although the systems are usually sized with an average power of 90 W/m^2 [25]. Therefore, the *Silvana-no-bio* house should incorporate a heating system and an air conditioning system with a minimum power of 10,796 W (269.9 m^2 * 40 W/m^2 = 10,796 W). In this way, the total power of the *Silvana-no-bio* electromechanical devices would be at least 15.320 W (10.796 W + 4.524 W) (Table 1), and its energy consumption (per m^2) would be 54.21 kWh/m^2/year (Table 3).

Silvana house consumes only 33.5% of what *Silvana-no-bio* would consume (18.21 kWh/m^2/year/

54.21 kWh/m^2/year), from which it follows that a good *bioclimatic architectural design* is capable of generating a minimum energy saving of 66.5%.

3.4 Reduction of the Economic Cost in the Energy Self-sufficiency of a Deep Bioclimatic House

A *deep bioclimatic house* like *Silvana* house doesn't need heating or air conditioning, as its special design allows it to self-regulate its internal temperature. Therefore, the house has very little need for electricity, and making it energy self-sufficient is very inexpensive.

To quantify the energy efficiency of a *deep bioclimatic house*, the energy consumption of the *Silvana house* is compared with the energy consumption of a conventional house of the same characteristics constructed in the same area. To be able to make a comparison we have compared *Silvana house* with respect to its hypothetical version as a baseline reference: *Silvana-no-bio*. That is, with an identical lifestyle, but with a conventional design and with average energy needs in the area. It is evident that, depending on your concrete design and your level of insulation and thermal inertia, each life can have a different energy consumption. For *Silvana-no-bio* it has achieved an average energy consumption in the area and with the same characteristics that *Silvana* house.

3.4.1 Economical Costs to Be Self-sufficient in Energy in a Deep Bioclimatic House. Silvana House

To achieve energy self-sufficiency at an affordable cost, a three-phase strategy has been followed:

1. Informing the owners to use as few devices as possible;
2. Carrying out an optimal *bioclimatic design*;
3. Correctly managing the devices incorporated into the house.

Due to its special deep *bioclimatic design*, *Silvana* house does not need heating or air conditioning. It is estimated that the maximum total power of all the devices that can be activated at the same time is 2,000 watts, with occasional peak requirements of up to 2,500 watts. To meet these needs, a photovoltaic system with ten photovoltaic solar collectors has been installed. This system generates approximately 3,500 watts at peak output, so that the batteries can provide a power of at least 2,500 W (as usual, batteries cannot supply their full power, but rather around 80%). This photovoltaic system costs €5,500 including VAT in Valencia.

3.4.2 Economical Costs to Be Self-sufficient in Energy in a Conventional House. Silvana-No-Bio

The total power of the *Silvana-no-bio* devices is 15,764 W, and, although not all devices have to be connected at the same time, the minimum power of the photovoltaic panels that should be installed to generate electrical energy for the house would be around 12,000 W. That is, for *Silvana-no-bio* to be self-sufficient in energy, four times as many photovoltaic panels would have to be installed than for *Silvana-bio*, and at an economic cost five 436% greater (around €24,000 including VAT) in Valencia.

It is thus essential to carry out an optimal *bioclimatic design* to achieve energy self-sufficiency at an affordable cost.

4. Discussion

The bioclimatic design of a building depends heavily on the architect's skill and experience, so the utilization of free energy resources varies and differs from one building to another. In some environments, only a small percentage of the energy consumption of buildings can be reduced by the bioclimatic design, while a large percentage can be reduced in others. In some cases, the bioclimatic design is so effective that heating and air conditioning systems are unnecessary, and this is referred to as *deep bioclimatic design*.

Of course, *deep bioclimatic buildings* can be designed more easily in more benign environments. However, specialist and experienced architects can also achieve *deep bioclimatic buildings* in more extreme environments. In these cases, a number of new architectural elements (greenhouses, cooling tubes, wind turbines, underground galleries, etc.) must be integrated into the buildings, which can substantially increase their cost. As a consequence, *deep bioclimatic buildings* are not very common. The additional cost of bioclimatic architectural elements is usually limited to the cost of the heating and air conditioning systems that are being avoided.

Consequently, with the appropriate knowledge and experience, *deep bioclimatic buildings* can be designed in any environment, regardless of the cost.

This study evaluated the energy efficiency of a *deep bioclimatic house*, *Silvana* House, whose design incorporates bioclimatic architectural systems whose cost is lower than the cost of the heating and air conditioning systems typically used in the surrounding area. Therefore, the results of the energy efficiency assessment of *Silvana* House can be extrapolated to houses with the same characteristics and built in similar environmental settings. They can also be extrapolated to houses and buildings built in different environments and with different characteristics, but in these cases the economic cost of the buildings may be considerably higher. Therefore, it would be interesting to conduct more case studies, like the present one, of houses and buildings built in different environmental settings.

5. Conclusions

This work shows that through a *deep bioclimatic design*, buildings capable of thermal self-regulation can be designed, providing a comfortable internal temperature without the need for heating or air conditioning. These buildings, because they consume very little energy, can become energy self-sufficient at a very low cost, requiring very few photovoltaic solar panels. A *deep bioclimatic house*, *Silvana* House, was analyzed, which requires only 33.5% of the average energy needed by any house of the same surface and characteristics in its surroundings. Due to its low energy requirements, *Silvana* house is energy self-sufficient at a cost of 23% of the cost required to make any house in its vicinity energy self-sufficient. The results of this work can be directly extrapolated to any *deep bioclimatic house* and serve as a conceptual reference for any *deep bioclimatic building*.

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